METHOD AND APPARATUS FOR INTERLEAVED OPTICAL SINGLE SIDEBAND MODULATION

BACKGROUND OF THE INVENTION

Cross-Reference to Related Applications

This application is a continuation-in-part of Application Serial No. 09/575,811 filed 5/22/2000, which claims the benefit of Provisional Application Serial No. 60/187,383 filed March 7, 2000, both applications of which are fully incorporated herein in their entirety.

Field of the Invention

The present invention relates generally to a method and apparatus for modulation of broadband optical signals, and more particularly to a method and apparatus for combining interleaved optical single sidebands with a modulated optical carrier.

Description of Related Art and General Background

Conventional optical fiber transmission systems, such as optical fiber community access television ("CATV") transmission systems can carry multiple channels on a single optical fiber communication line. The channels are transmitted modulated on a wideband signal made up of a plurality of frequency division multiplexed carriers. A wideband optical detector or photo-receiver receives the wideband signal. Each individual channel can be recovered by a heterodyne tuner along with an appropriate microwave filter. An optical fiber transmission system using this type of modulation technique can transmit analog or digital signals and is known as a sub-carrier multiplexed ("SCM") optical transmission system. Figure 1 shows a schematic diagram of a typical SCM system which is described in detail in W. I. Way, Subcarrier Multiplexed Lightwave Systems for

Subscriber Loop Applications, Journal of Lightwave Technology, 1988, pp. 1806-1818.

High spectral efficiency digital modems may be used to greatly increase the spectral efficiency of conventional SCM techniques. For example, an optical transmitter with a 1GHz bandwidth can transmit 166 sub-carrier 6MHz 64-QAM (quadrature amplitude modulation) channels. Since each channel can carry 30 Mb/s of data, 4.98 Gb/s of data may be transmitted, which gives a spectral efficiency of approximately 5 bits/sec/Hz. In comparison, the same transmitter can transmit only 1.4 Gb/s of on-off keying data for a spectral efficiency of only about 1.4 bits/sec/Hz.

There are two important problems to overcome when using a broadband optical transmitter to transport a large quantity of digital data using SCM technology. The first is that the receiver must be a very wideband photoreceiver, which tend to have high spectral noise density and require a complicated and expensive heterodyne receiver. The second is that SCM is an optical double-sideband modulation (ODSB) technique, as shown in Figure 2A. This means that half of the bandwidth is wasted, as each of the upper and lower sidebands are carrying the same information. One solution to this problem, as shown in Olshansky (U.S. Pat. No. 5,301,058), is to eliminate the lower side band to produce an optical single-sideband signal (OSSB) as shown in Figure 2B. One may then combine many OSSB modulators, using multiple carrier signals, to more efficiently use the available optical fiber transmission spectrum. This is illustrated in Figure 2C. This is known as OSSB-DWDM, or optical single side band, dense wavelength division multiplexing. Using double OSSB (D-OSSB), the upper and lower sidebands carry different signals, as shown in Figure 2D. Thus, the required number of carriers is only half of that required by the OSSB modulation shown in Figure 2C.

When amplifying the transmitted signal in a conventional multiplexing method, the carrier signal is likewise amplified. Amplification of the carrier signal represents a waste of amplifier gain, since gain is used to amplify a signal that carries no information. Moreover, as power density in the transmission fiber is increased, signal distortions due to optical nonlinear effects are also increased. Elimination of the carrier signal can significantly decrease the total signal power, thereby reducing the total power density and nonlinear effects.

One method for suppressing the carrier is disclosed by Olshansky (U.S. Pat. No. 5,301,058) and Price (U.S. Pat. No. 6,118,566). However, the method requires a pair of Mach Zehnder interferometers and a pair of microwave modulators to generate just two sidebands. The apparatus is complicated and costly.

Yet another method for suppressing the carrier signal is disclosed by Jopson (U.S. Pat. No. 5,745,273). Jopson makes use of a dual path modulator arranged in an optical loop. The light is divided by a coupler which provides a portion of the signal to an optical fiber traveling in each direction around the loop. The signal in one direction is modulated to create a carrier and sidebands while the other is solely the carrier. Upon recombining the two optical signals in a combiner, a signal is produced in which the two carrier signals cancel each other and leave only the modulated signal. One drawback of the Jopson arrangement is the requirement of extremely strict tolerances with respect to the lengths of the paths of the loop so that the two signals will arrive at the combiner having the carrier signals exactly out of phase. This requirement makes the Jopson device difficult to implement in practice.

Another important fact is that the suppressed optical carrier implies a waste of optical power. Therefore, it is preferred to re-use the optical carrier by modulating it with a new baseband data channel.

Even these solutions are imperfect. Use of an OSSB suppressed carrier (OSSB-SC) modulation method, when applied to multi-channel, long-distance optical fiber transmission systems, presents three additional problems. First, conventional narrowband optical filters have a slow roll-off which makes it likely that an optical filter used in the receiver will allow portions of adjacent channels to enter into the filtered window, producing noise in the signal, as illustrated in Figures 3A and 3B. Second, as illustrated in Figure 3B, residual images are produced due to imperfections in the 90° phase shift of the high frequency electrical modulating signal or in the phase shift of the optical signal between the arms of the Mach-Zehnder modulator. Third, dispersion causes self- and external phase modulations which tend to produce distortions in signals transmitted over long distances at 1550nm, due to beating among the several optical channels, e.g., four-wave mixing products. This last problem may be reduced by the use of conventional dispersion reduction techniques such as use of a chirped fiber grating or dispersion compensating fibers. However, both of these conventional techniques are costly and cannot manage the entire wavelength range.

To avoid residual images and optical nonlinearity-induced distortions, there is a need to use interleaved optical single sidebands, or optical single sidebands having unequal spacing between neighboring channels. To suppress the optical carrier and yet still re-use it, there is a need for an optical carrier notch filter that combines interleaved optical single sidebands with a modulated optical carrier.

SUMMARY OF THE INVENTION

Accordingly, an object of the present invention is to provide an optical single sideband modulator which produces an optical carrier and interleaved single sidebands or single sidebands with unequal channel spacing.

Another object of the present invention is to provide an improved optical carrier notch filter whose reflected part contains the interleaved single sidebands with a suppressed optical carrier, and whose transmission part contains the optical carrier.

A further object of the present invention is to provide a method and apparatus that remotely notches out or re-inserts an optical carrier.

Yet another object of the present invention is to provide a method of modulating an optical carrier with a baseband signal with a baseband modulator.

Another object of the present invention is to provide optical combiner that combines interleaved optical single sidebands with a modulated optical carrier.

A further object of the present invention is to provide a method of separating interleaved sideband signals from an optical carrier and modulating the optical carrier to create a modulated optical carrier.

These and other objects of the present invention are achieved in an optical carrier notch filter. An optical coupler is provided that includes at least first, second and third ports. The first port is configured to receive an output that includes an optical carrier and interleaved optical single sideband signals. An optical bandpass filter is coupled to a port of the optical coupler. The optical bandpass filter separates the output into a transmitted signal that contains the optical carrier, and a reflected signal that includes the interleaved optical single sideband signals. The reflected signal is reflected from the optical bandpass filter to the third port of the optical coupler.

In another embodiment of the present invention, an optical carrier notch filter includes an optical coupler with at least first, second and third ports. The first port is configured to receive an output that includes an optical carrier and interleaved optical single sideband signals. An optical narrowband-reject filter is coupled to a port of the optical coupler. The

optical narrowband-reject filter separates the output into a reflected signal that contains the optical carrier and a transmitted signal that includes the interleaved optical single sideband signals that are transmitted through the optical narrowband-reject filter.

In another embodiment of the present invention, an optical carrier notch filter includes a multiple port circulator with at least first, second and third ports. An optical narrowband-reject filter is coupled to the second port of the multiple port circulator. The optical narrowband-reject filter separates an output received from the circulator into a transmitted signal that contains an optical carrier and a reflected signal that includes interleaved optical single sideband signals. The reflected signal is reflected from the optical narrowband-reject filter to the third port of the circulator.

In another embodiment of the present invention, an optical carrier notch filter includes a multiple port circulator with at least first, second and third ports. An optical narrowband-reject filter is coupled to the second port of the multiple port circulator. The optical narrowband-reject filter separates an output received from the circulator into a reflected signal that contains an optical carrier and a transmitted signal that includes interleaved optical single sideband signals. The transmitted signal is transmitted through the optical narrowband-reject filter.

In another embodiment of the present invention, an interleaved optical single sideband communications system includes a Mach-Zehnder modulator constructed and arranged to accept an incoming optical carrier. The Mach-Zehnder includes a splitter which splits the incoming optical signal into a first optical carrier and a second optical carrier. A first AC phase modulator applies a first electrical signal carrying a plurality of first channels and modulates the first optical signal. A second AC phase modulator applies a second electrical signal carrying a plurality of second channels and modulates the second optical signal. Each first channel corresponds to one of the second channels. Each first channel is phase

shifted 90° relative to each corresponding second channel. A first DC phase modulator modulates the first optical signal. A second DC phase modulator modulates the second optical signal. The first and second DC phase modulators are constructed and arranged to modulate an optical carrier component of the first optical signal to be phase shifted 90° relative to an optical carrier component of the second optical signal. The optical carrier component of the second optical signal has a frequency substantially equal to the optical carrier component of the first optical signal. A directional coupler is coupled to the Mach-Zehnder modulator and combines the modulated first and second optical signals to form a combined optical signal having an optical carrier component. Alternate channels of the combined optical signal are substantially cancelled. The Mach-Zehnder modulator creates a first single side band on a side of the optical carrier frequency, a first residual image on the opposite side of the optical carrier frequency, a second side band on a side of the optical carrier frequency, and a second residual image on the opposite side of the optical carrier frequency.

In another embodiment of the present invention, an interleaved optical single sideband communications system includes a Mach-Zehnder modulator constructed and arranged to accept an incoming optical carrier. The Mach-Zehnder modulator includes a splitter that splits the incoming optical signal into a first optical carrier and a second optical carrier. A first AC phase modulator applies a first electrical signal carrying a plurality of first channels and modulates the first optical signal. A second AC phase modulator applies a second electrical signal carrying a plurality of second channels and modulates the second optical signal. Each first channel corresponds to one of the second channels. Each first channel is phase shifted 90° relative to each corresponding second channel. A first DC phase modulator modulates the first optical signal. A second DC phase modulator modulates the second optical signal. The first and second DC phase modulators are constructed and arranged to modulate an optical carrier

component of the first optical signal to be phase shifted 90° relative to an optical carrier component of the second optical signal. The optical carrier component of the second optical signal has a frequency substantially equal to the optical carrier component of the first optical signal. A combiner combines the modulated first and second optical signals to form a combined optical signal having an optical carrier component. Alternate channels of the combined optical signal are substantially cancelled. A notch filter is coupled to the Mach-Zehnder modulator. The notch filter includes an optical coupler with at least first, second and third ports. The first port is configured to receive an output that includes an optical carrier and interleaved optical single sideband signals. An optical bandpass filter is coupled to a second port of the optical coupler. The optical bandpass filter separates the output into a transmitted signal that contains the optical carrier and a reflected signal that includes the interleaved optical single sideband signals. The reflected signal is reflected from the optical bandpass filter to the third port of the optical coupler.

In another embodiment of the present invention, An interleaved optical single sideband communications system includes a Mach-Zehnder modulator that is constructed and arranged to accept an incoming optical carrier. The Mach-Zehnder modulator includes a splitter which splits the incoming optical signal into a first optical carrier and a second optical carrier. A first AC phase modulator applies a first electrical signal carrying a plurality of first channels and modulates the first optical signal. A second AC phase modulator applies a second electrical signal carrying a plurality of second channels and modulates the second optical signal. Each first channel corresponds to one of the second channels. Each first channel is phase shifted 90° relative to each corresponding second channel. A first DC phase modulator modulates the first optical signal. A second DC phase modulator modulates the second optical signal. The first and second DC phase modulators are constructed and arranged to modulate an optical carrier

component of the first optical signal to be phase shifted 90° relative to an optical carrier component of the second optical signal. The optical carrier component of the second optical signal has a frequency substantially equal to the optical carrier component of the first optical signal. A combiner combines the modulated first and second optical signals and forms a combined optical signal with an optical carrier component. Alternate channels of the combined optical signal are substantially cancelled. A notch filter coupled to the Mach-Zehnder modulator. The notch filter includes an optical coupler with at least first, second and third ports. The first port being configured to receive an output that includes an optical carrier and interleaved optical single sideband signals, and an optical narrowband-reject filter coupled to a second port of the optical coupler. The optical narrowband-reject filter separates the output into a reflected signal that contains the optical carrier and a transmitted signal that includes the interleaved optical single sideband signals. The transmitted signal is transmitted through the optical narrowband-reject filter.

In another embodiment of the present invention, an interleaved optical single sideband communications system. A single Mach-Zehnder modulator is constructed and arranged to accept an incoming optical carrier. The Mach-Zehnder modulator includes a splitter which splits the incoming optical signal into a first optical carrier and a second optical carrier. A first AC phase modulator applies a first electrical signal carrying a plurality of first channels to modulate the first optical signal. A second AC phase modulator applies a second electrical signal carrying a plurality of second channels to modulate the second optical signal. Each first channel corresponds to one of the second channels. Each first channel is phase shifted 90° relative to each corresponding second channel. A first DC phase modulator to modulate the first optical signal. A second DC phase modulator modulates the second optical signal. The first and second DC phase modulators are constructed and arranged to modulate an optical

carrier component of the first optical signal to be phase shifted 90° relative to an optical carrier component of the second optical signal. The optical carrier component of the second optical signal has a frequency substantially equal to the optical carrier component of the first optical signal. A combiner combines the modulated first and second optical signals to form a combined optical signal having an optical carrier component. Alternate channels of the combined optical signal are substantially cancelled. The Mach-Zehnder modulator creates a first single side band on a side of the optical carrier frequency with a first residual image on a side of the optical carrier frequency, and a second side band on a side of the optical carrier frequency with a second residual image on a side of the optical carrier frequency. A frequency of the first side band is offset from the second residual image, and a frequency of the second side band is offset from the first residual image.

In another embodiment of the present invention, a method of modulating an optical carrier includes receiving an output that has an optical carrier and interleaved sideband signals. The interleaved sideband signals are separated from the optical carrier. The optical carrier is modulated to create a modulated optical carrier.

In another embodiment of the present invention, a method of re-inserting an optical carrier at a remote location in a network includes receiving an output that has an interleaved sideband signals with a suppressed optical carrier. An optical carrier is combined with the same wavelength as the suppressed optical carrier and the interleaved sideband signals at a remote network site.

In another embodiment of the present invention, a method of re-modulating or suppressing an optical carrier at a remote location in a network includes receiving an output that has an optical carrier and interleaved sideband signals. The interleaved sideband signals are separated

from the optical carrier at a remote network site. The optical carrier is modulated to create a modulated optical carrier or notched out.

In another embodiment of the present invention, a method of modulating an optical carrier frequency in a Mach Zehnder interferometer modulator that has a first phase modulator and a second phase modulator includes splitting a power of the optical carrier frequency into a first portion and a second portion. The first portion of the carrier signal frequency is introduced to the first phase modulator and the second portion of the carrier signal frequency is introduced to the second phase modulator. A first signal is applied to the first phase modulator at a first phase and to the second phase modulator at a second phase. A first single side band is created on a side of the optical carrier frequency. A first residual image is created on a side of the optical carrier frequency. A second signal is applied to the first phase modulator at a first phase and to the second phase modulator at a second phase. A second side band is created on a side of the optical carrier frequency. A second residual image is created on a side of the optical carrier frequency. A frequency of the first side band is offset from the second residual image, and a frequency of the second side band is offset from the first residual image.

In another embodiment of the present invention, a method of transmitting a plurality of channels provides a plurality of electrical signals. Each electrical signal corresponds to a channel. First and second split signals are produced that correspond to each of the plurality of signals. Each first split signal is substantially at quadrature with a corresponding second split signal. An optical carrier signal is provided. The optical carrier signal is multiplexed with the split signals to produce a multiplexed optical signal. Alternate channels are substantially cancelled and residual images of upper side band channels do not substantially overlap channels carried on a lower side band.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of a conventional subcarrier multiplexed lightwave system.

Figures 2A through 2D are spectral diagrams comparing spectral efficiency of various modulation techniques.

Figure 3A is a spectral diagram showing optical double sideband transmission.

Figure 3B is a spectral diagram showing optical single sideband transmission.

Figure 3C is a spectral diagram showing interleaved optical single sideband transmission according to the present invention.

Figure 4A is a schematic diagram of an optical frequency division multiplexed lightwave system according to the present invention.

Figure 4B is a schematic diagram of an optical frequency division multiplexed lightwave system having an array of optical filters according to the present invention.

Figure 4C is a schematic diagram of an optical frequency division multiplexed lightwave system including a broadband optical receiver according to the present invention.

Figure 5A is a schematic diagram of a prior art dual electrode Mach-Zehnder modulator.

Figure 5B is a spectral diagram showing input and output of the modulator shown in Figure 5A.

Figure 5C is a schematic diagram of a dual-electrode Mach-Zehnder modulator as employed in the present invention.

Figure 5D is a spectral diagram showing input and output of the modulator shown in Figure 5C.

Figure 6A shows a four channel dual-electrode Mach-Zehnder modulator as employed in the present invention.

Figures 6B-6E show spectral diagrams of input and output signals from the modulator shown in Figure 6A.

Figure 7 is a schematic diagram showing an interleaved optical single sideband suppressed carrier optical transmitter according to the present invention.

Figure 8 is a schematic diagram of a transmitter according to the present invention.

Figure 9 is a schematic diagram of a multiple light source optical communication system according to the present invention.

Figure 10 is a schematic diagram of one embodiment of a notch filter, and the re-modulation of an optical carrier, of the present invention.

Figure 11 is a schematic diagram of detection methods useful with the Figure 10 transmitter.

Figure 12 is a schematic diagram illustrating how cascaded directional couplers can be used to combine multiple $0^{\circ}/90^{\circ}$ microwave modulation signals with a baseband modulation signal.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the following description, for purposes of explanation and not limitation, specific details are set forth such as particular optical and electrical circuits, circuit components, techniques, etc. in order to provide a thorough understanding of the present invention. However, the invention may be practiced in other embodiments that depart from these specific details. In some instances, detailed descriptions of well-known devices and circuits may be omitted so as not to obscure the description of the present invention with unnecessary details.

In one embodiment of the present invention, an interleaved optical single sideband communications system includes a single Mach-Zehnder modulator, constructed and arranged to accept an incoming optical carrier.

A splitter splits the incoming optical signal into a first optical carrier and a second optical carrier. A first AC phase modulator applies a first electrical signal carrying a plurality of first channels to modulate the first optical signal. A second AC phase modulator applies a second electrical signal carrying a plurality of second channels to modulate the second optical signal. Each first channel corresponding to one of the second channels and is phase shifted 90° relative to each corresponding second channel. A first DC phase modulator modulates the first optical signal. A second DC phase modulator modulates the second optical signal. The first and second DC phase modulators are constructed and arranged to modulate an optical carrier component of the first optical signal to be phase shifted 90° relative to an optical carrier component of the second optical signal. The optical carrier component of the second optical signal has a frequency equal to the optical carrier component of the first optical signal. A combiner combines the modulated first and second optical signals to form a combined optical signal having an optical carrier component such that alternate channels of the combined optical signal are substantially cancelled. The single Mach-Zehnder modulator creates an optical carrier, a first single side band on a side of the optical carrier frequency with harmonic signals on the same side of the optical carrier frequency, and with a first residual image on the other side of the optical carrier frequency, a second side band on a side of the optical carrier frequency with harmonic signals on the same side of the optical carrier frequency, and with a second residual image on the other side of the optical carrier frequency. A frequency of the first side band is offset from the harmonics and residual image of the second sideband, and a frequency of the second side band is offset from the harmonics and the residual image of the first sideband.

In another embodiment of the present invention, a method of modulating an optical carrier frequency in a Mach Zehnder interferometer modulator splits a power of the optical carrier frequency into a first portion

and a second portion. The first portion of the carrier signal frequency is introduced into a first phase modulator and the second portion of the carrier signal frequency is introduced into a second phase modulator. A first signal is applied to the first phase modulator at a first phase and to the second phase modulator at a second phase. A first single side band and its harmonics are created on a side of the optical carrier frequency. A first residual image is created on the other side of the optical carrier frequency. A second signal is applied to the first phase modulator at a first phase and to the second phase modulator at a second phase. A second side band and its harmonics are created on a side of the optical carrier frequency. A second residual image is created on the other side of the optical carrier frequency. A frequency of the first side band is offset from the residual image and harmonics of the second sideband, and a frequency of the second side band is offset from the residual image and harmonics of the first sideband. Frequencies of the first sideband and the second sideband are also offset from any four-wave mixing products of the two sidebands.

Referring now to Figure 1, a conventional subcarrier multiplexing transmitter and receiver pair are shown. A plurality of modulators 2, 4, 6, 8, which may be analog, digital or any combination thereof, produce signals corresponding to a plurality of channels. Each channel is frequency division multiplexed by using local oscillators 10, 12, 14, 16 of different radio frequencies, known as subcarriers. The signal for each channel is processed by a band pass filter (not shown) to attenuate components of the signal which are outside of the channel (e.g. harmonics). The several channels are amplified by an amplifier 26 and combined, and the combined signal is amplified once more and used to drive a light emitting device which is conventionally a directly or externally modulated laser diode acting as part of an optical transmitter 36. Preferably the light emitting device has a fast response time and can produce a narrow linewidth with good coherence.

The combined signal is transmitted through an optical fiber 38 to a broadband optical receiver 40. The optical fiber 38 is preferably single mode fiber to reduce modal dispersion and other modal noise problems. It may alternately be a conventional single mode fiber having zero dispersion at 1310nm or any other single mode fiber. For wavelength division multiplexing applications, or other broadband applications, the dispersion slope is also preferably small. The signal proceeds to a heterodyne tuner which typically includes a tunable local oscillator 46 which is used to selectively tune to one of the channels which may then be demodulated with an appropriate analog or digital demodulator. Preferably, a band pass filter (not shown) may be included in the receiver to better select the desired channel and exclude noise from neighboring channels. The final detection process can be either coherent or incoherent demodulation.

Figure 4A shows a multiple channel transmission system consistent with an aspect of the present invention. Baseband signals are modulated by a plurality of modulators 52, 54, 56. The modulators may be, for example, a simple modulator such as an amplitude shifted keying (ASK) modulator, a frequency shifted keying (FSK) modulator, a differential phase shift keying (DPSK) modulator, a differential quadrature phase shift keying (DQPSK) modulator, or a duobinary modulator.

The modulated signals are each passed through an intermediate frequency band pass filter 58, 60, 62, then modulated using a plurality of upconverters including local oscillators 64, 66, 68. The channels are combined, amplified and passed through an amplifier 70 to an optical transmitter 72 which may be optical transmitter 36 described above with respect to Figure 1. Optionally, the transmitter 72 may include an erbium-doped fiber amplifier (EDFA, not shown) to increase the signal strength. The combined optical signal passes through a length of optical fiber 74, which is preferably single mode optical fiber. It is optionally pre-amplified with an optical amplifier 76, which is preferably an EDFA. A tunable or

fixed channel optical filter 78 selects a particular channel which is then received by a baseband optical receiver 80. The optical filter 78 also helps to reduce spontaneous emission noise produced by the EDFA pre-amplification process. The baseband optical receiver 80 produces an electrical signal which is demodulated by a demodulator 82.

A second embodiment of a transmission system is shown in Figure 4B. The system shown in Figure 4B is similar to the system of Figure 4A. However, the single tunable optical filter 78 is replaced by a plurality of optical filters 84, 86, 88 each of which is preferably a fixed filter, although each may also be tunable filters adapted to pass only a single selected channel. Each channel signal proceeds to a baseband optical receiver 90, 92, 94 which in turn, passes the resulting electrical signal to a demodulator 82.

Where tunable filters are used, they preferably include a feedback circuit to ensure that the filter passband always locks on to the center of the desired channel, despite any wavelength drift of the laser diode. This provides an advantage over conventional DWDM systems in which all optical transmitters require a stringent wavelength locker. It is also possible that the filter passband is offset from the center of the digital modulated signal passband to eliminate some of its sideband so that the dispersion penalty can be decreased. Note that the tunable optical filter cannot differentiate one channel from the other simply based on locking onto optical power, since all channels have essentially the same optical power. To ensure that the tunable filter can selectively tune to a specific channel, a channel-specific identification information should be built in both the transmitter and the receiver.

Another alternate arrangement of the transmission system is shown in Figure 4C. In this embodiment, one of the channels carries a plurality of low bit-rate channels 96, 98, 100. The plurality of low bit-rate subcarrier channels 96, 98, 100 are multiplexed onto a single band having a bandwidth

which is preferably of a similar size to each of the high bit-rate channels, though this is not necessary. Other components of the device are similar to those shown in FIGS. 4A and 4B, with the exception of the receivers. For each channel which contains low bit-rate subcarrier channels, the baseband optical receiver 90 is replaced with a broadband optical receiver 102. The broadband optical receiver 102 provides the sub-channel signals to demodulators (not shown) which are then used to extract each of the individual sub-channels.

The plurality of low bit-rate channels shown in Figure 4C can preferably use spectrally efficient modems (96, 98, 100) such as M-ary quadrature amplitude modulated (QAM) modems, quadrature phase shifted keying (QPSK) modems, orthogonal frequency division multiplexing (OFDM) modems or M-ary vestigial sideband (VSB) modems. One skilled in the art will recognize that other spectrally efficient modems may be employed.

To better understand the present invention, it is useful to discuss OSSB and D-OSSB transmission. In an OSSB system carrying one channel, the channel is modulated onto the optical carrier signal with a modulator shown in detail in Figures 5A and 5B. A dual electrode Mach-Zehnder modulator, indicated generally at 104, forms the basis of the system. An incoming light signal λ_{IN} is split into a first optical signal λ_1 and a second optical signal λ_2. An RF alternating current electrode 106 modulates the two optical signals with the channel signal to be transmitted (i.e. f_1), however, f_1 is applied to the carrier such that the signal applied to the upper arm of the modulator is phase-shifted 90° with respect to the signal applied to the lower arm. Subsequently, a DC electrode 108 further modulates the carriers such that the two arms are also shifted 90° with respect to each other. That is, the carriers of the two arms are in quadrature with each other. The two signals are then combined to produce an output

signal λ_{OUT} in which only the carrier and the lower side band are present. This process may be easily modified so that the lower side band is cancelled and the upper side band is transmitted.

Referring now to Figure 5B, spectra of the signals at various stages are shown. Initially, λ_{IN} includes only the carrier. After both the AC and DC electrodes 106, 108 have applied an electric field to the carrier signal in the upper arm, λ_1 has an upper and a lower side band, the upper side band at 90° and the lower side band at -90°, along with the carrier at 0°. Likewise, after passing through both electric fields, the lower arm signal λ_2 has a carrier at -90°, an upper side band at -90° and a lower side band at -90°. When the two signals λ_1 and λ_2 are combined to form λ_{OUT} the two upper side bands cancel each other, leaving only the lower side band and the carrier.

Figures 5C and 5D illustrate D-OSSB transmission. Just as in OSSB, a dual-electrode Mach-Zehnder modulator 104 is used. An incoming light signal λ_{IN} is split into a first optical signal λ_1 and a second optical signal λ_2. An RF alternating current electrode 106 is used to modulate the two optical signals with a first channel m1, to be transmitted, however, the signal is applied to the carrier in such a way that the m1 component of the first and second optical signals are phase-shifted 90° with respect to each other. At the same time, the RF alternating current modulates the two optical signals with a second signal m2, with the m2 component of the first and second optical signals phase-shifted 90° with respect to each other. Moreover, in each arm of the modulator, m1 is phase-shifted 90° with respect to m2. Subsequently, a DC electrode 209 further adjusts the phases of the carriers such that the two arms are also shifted 90° with respect to each other, that is the carriers of the two arms are in quadrature with each other. The two signals are then combined to produce

an output signal λ_{OUT} in which contains the carrier, m2 as the upper side band and m1 as the lower side band.

As shown in Figure 5D, λ_{IN} includes only the carrier. After both the AC and DC electrodes have applied an electric field to the carrier signal in the upper arm, λ_1 can be represented by the sum of the two spectra shown. A first spectrum of λ_1 has an upper and a lower side band each carrying m1, the upper side band at 90° and the lower side band at -90°, along with the carrier at 0°. A second, carrying m2, has an upper side band at 0° and a lower side band also at 0°. Likewise, after passing through both electric fields, the lower arm signal λ_2 can be represented by the sum of two spectra. A first λ_2 spectrum carrying m1 has a carrier at -90°, an upper side band at -90° and a lower side band at -90°. A second, carrying m2, has a carrier at -90°, an upper side band at 0° and a lower side band at -180°. When the two signals λ_1 and λ_2 are combined to form λ_{OUT} the two upper side bands of m1 cancel each other, leaving only the lower side band and the carrier. Similarly, the two lower m2 sidebands cancel each other, leaving only the upper side band and the carrier. Thus, λ_{OUT} contains the carrier and the two side bands, the lower carrying m1 and the upper carrying m2. The system can be easily modified to reverse the order such that the lower side band will carry m2 and the upper will carry m1.

As discussed above, ODSB transmission has the drawback that an optical filter will have a spectrum 109 which tends to overlap multiple channels, introducing noise into the decoded signal, as shown in Figure 3A. Further, ODSB requires allocating one-half of the bandwidth to images of the primary information since each side band carries the same information. As shown in Figure 3B, the OSSB technique shown in Figures 5A-B fail to completely solve these problems. Though the lower side band is available for additional channels as in D-OSSB, the problem with the filter overlap remains, and a second problem is introduced. Since it is difficult to produce

perfect quadrature in the multiplexer, cancellation of the unwanted side band will often be incomplete, resulting in residual images 110. These residual images 110 produce additional noise, which when added to the noise resulting from the filter's slow roll off, can seriously interfere with reception of the transmitted data.

As shown in Figure 3C, by interleaving channels with empty channels, the problem of slow band bass filter roll off can be eliminated and the problem of residual images can be substantially reduced. Since no channel is directly adjacent to another, the filter can properly capture a single channel without also picking up portions of the neighboring ones. Since there are only two residual images 110 on each side band (in this example using four channels), the filter will pick up a smaller amount of noise from the images. Note how in Figure 3C, only tails of each residual image are within the filter range 109. In contrast, in Figure 3B, nearly two entire residual images are within the filter range 109. Even more importantly, the system penalty due to optical nonlinearity-induced four-wave mixing can also be minimized using this technique.

A modulator consistent with the present invention for interleaving channels to produce I-OSSB modulation is illustrated in Figures 6A-E. An input optical signal λ_{IN}, includes only the carrier as shown in Figure 6B. The AC electrode 106 of a Mach-Zehnder multiplexer 104 applies an electric field to the carrier signal in the upper arm, λ_1 containing the channels to be transmitted. After further application of a DC field by the DC electrode 108, the output can be represented by the spectrum shown in Figure 6C. Four separate signals f_1, f_2, f_3, and f_4 are multiplexed onto the carrier, each producing both an upper side band and a lower side band. Adjacent channels are 90° out of phase with each other.

Similarly, the lower arm has four separate signals f_1, f_2, f_3, and f_4 multiplexed onto the carrier, as shown in Figure 6D. Each of the signals, f_1,

f_2, f_3, and f_4, is applied to the lower arm in quadrature with the corresponding signal f_1, f_2, f_3, and f_4 in the upper arm and each is 90° out of phase with its adjacent channel. Each arm is then placed in quadrature with the other by the DC electrode 108.

When the two signals λ_1 and λ_2 are combined to form λ_{OUT} the f_1 and f_3 signals are cancelled in the upper side band, leaving only f_2 and f_4. Likewise, in the lower side band, f_2 and f_4 signals are cancelled leaving only f_1 and f_3. Thus, λ_{OUT} contains the carrier and the two side bands, the lower side band carrying f_1 and f_3 and the upper side band carrying f_2 and f_4. The system can be easily modified to reverse the order such that the lower side band will carry f_2 and f_4 and the upper will carry f_1 and f_3. As can be appreciated from the spectrum shown in Figure 6E, this result corresponds to the spectrum shown in Figure 3C and each channel has no directly adjacent channels, that is, every other channel has been cancelled.

The I-OSSB modulator of Figures 6A-E may be used in a transmission system as illustrated in Figure 7. A continuous wave light source 112, such as a laser diode, produces a light signal. The light signal passes through a polarization controller 114 or a polarization maintaining optical fiber 115 which maintains a particular polarization of the light. The light signal is processed by an I-OSSB optical modulator 116 as described above, producing, in the example as shown, four multiplexed channels. A local or remote notch filter 118 is disposed downstream from the modulator 116. The notch filter 118 is a bandreject filter which is selected to eliminate the carrier without interfering with the signals of the channels. Optionally, an EDFA amplifier 120 may follow the notch filter 118 to boost the signal strength. When the transmission distance of a system is extremely long, the system could include a dispersion compensating device 122 which helps to reduce the signal loss and distortion due to dispersion and intermodulation (i.e. four wave mixing). This dispersion compensating device 122 may be,

for example, a chirped fiber Bragg grating (CFBG), as shown in the Figure, in which the period of the grating varies linearly with position. As a result, the grating reflects different wavelengths at different points along its length which produces a wavelength dependent delay in the signal. In a wide band application, it may be necessary to employ multiple CFBGs in order to produce sufficient delay across a broad frequency range. Alternately, a dispersion compensating fiber may be used, however, dispersion compensating fibers generally have the drawback that attenuation is very high. After passing through the dispersion compensating component 122, the signal may be amplified again by an amplifier 120, then it is transmitted through the optical fiber 123, which is preferably a single mode fiber. It should be noted that all these dispersion compensation devices may not be needed when the transmission distance is not long enough to generate significant dispersion penalties.

Figure 8 shows additional detail of the electrical portion of a transmitter according to the present invention. A plurality of baseband encoders, for purposes of illustration, four, 124, 126, 128, 130 produce a signal for each of a plurality of channels. Each channel signal is preferably filtered with a low pass filter 132, 134, 136, 138 prior to upconversion by a local oscillator 140, 142, 144, 146. Next, the signals are preferably filtered again with a band pass filter 148, 150, 152, 154 prior to optional amplification by an amplifier 156. A hybrid coupler 164 is used to split each channel into two signals at 90° to each other. Two of the 90° signals are passed to a first summer 166 and two to a second summer 168. Likewise, two of the 0° are passed to each summer 166, 168. By way of example, the 90° of channels 1 and 3 are passed along with the 0° of channels 2 and 4 to the first summer 166, while the 90° of channels 2 and 4 are passed along with the 0° of channels 1 and 3 to the second summer 168. The summed signals may then be used to modulate a light signal from light emitting device 168 at the carrier frequency in a dual-arm Mach-Zehnder

modulator 170 as shown in Figures 6A-E. Summers 166 and 168 may also be replaced by wideband microwave/millimeter wave directional couplers, as illustrated in Figure 12, to increase the number of combined channels and add an additional baseband signal.

It may be useful in practice to provide a system according to the present invention which combines the I-OSSB modulator with dense wavelength division multiplexing to provide extremely high bandwidth transmission, as shown in Figure 9. A plurality of light emitting devices 172, 174, 176, 178 supply carrier signals for a plurality of I-OSSB modulators 180, 182, 184, 186, each transmitting multiple channels. The multiplexed signals are preferably passed through a dispersion compensating device 188 before or preferably after entering a multiplexer 190, which may be of conventional design.

Multiplexer 190 can also be replaced by a wideband optical coupler whenever applicable. The multiplexed signal is transmitted over a single mode fiber 192 and treated, as appropriate, with an amplifier 194 such as an EDFA. A demultiplexer 196, which may be of conventional design, separates the carrier signals, which are then filtered by an optical filter 198 and received with a receiver 200 according to the present invention, such as is shown in Figure 4B or 4C. In place of a conventional demultiplexer 196, the demultiplexer 196 may be custom designed to accommodate various wavelength windows.

Referring now to Figure 10, one embodiment of notch filter 118 is illustrated. In this embodiment notch filter 118 is coupled to dual electrode Mach-Zehnder modulator 104. An optical coupler 210 includes at least first, second and third ports 212, 214, and 216, respectively. In one embodiment optical coupler 210 is a circulator. An optical bandpass filter 218 is coupled to second port 214. Preferably, optical bandpass filter 218 is a narrowband filter (e.g., based on fiber gratings or Fabry-Perot cavity) that is centered at the wavelength of the carrier signal. Optical bandpass filter

218 separates the output into a transmitted signal and a reflected signal. The transmitted signal contains the optical carrier. The reflected signal includes the interleaved optical single sideband signals that are reflected from optical bandpass filter 218 to third port 216. An external modulator 220, which can be but is not limited to a Mach Zehnder, is coupled to optical bandpass filter 218. A baseband signal is applied to the external modulator 220 to modulate the optical carrier and create a modulated optical carrier.

Notch filter 118 can be positioned adjacent to Mach-Zehnder modulator 104 or at a remote location in an optical network.

The optical carrier transmitted through optical bandpass filter can be re-utilized with an additional baseband signal that modulates the optical carrier via the baseband external modulator.

A coupler 222 can be coupled to third port 216 and external modulator 220, the coupler combining the modulated optical carrier with the interleaved optical single sideband signals.

The optical signal at point 224 includes the interleaved optical single sideband signals and the original optical carrier. At point 226, the optical signal includes only the interleaved optical single sideband signals. At point 228, the output signal includes the interleaved optical single sideband signals and the modulated optical carrier.

After the output 226 is launched into an optical network, an optical carrier can be re-inserted in a remote network when there is a need for broadband detection, as illustrated in Figure 1. The broadband detection with simple incoherent microwave demodulators could eliminate narrowband optical filters in Fig.11 and consequently save significant cost.

In Figure 11, the optical signals at points 224, 226 and 228 can be detected by an optical filter 230 coupled to a photo-detector 232 and a baseband trans-impedance amplifier 234. This is basically the same type of baseband receiver as conventional on-off keyed non-return-to-zero (NRZ) signals. The optical signal from point 224 can be detected with a broadband

photo-detector 236 in combination with individual microwave channel detectors 238 which could be coherent or incoherent detection. In this case, the transmitter and receiver arrangement are very similar to conventional subcarrier multiplexed lightwave system, except that the transmitter now is an optical single sideband modulator rather than an optical double sideband modulator.

Referring now to Figure 12, cascaded directional couplers 240 are coupled to Mach-Zehnder modulator 170 and replace summers 166 and 168.

Using cascaded directional couplers to replace summers to couple in signal power channel by channel can provide a better isolation between channels, and in the same time they are more scaleable than summers and provides the option of adding an additional baseband channel.

While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not limited to the disclosed embodiment, but on the contrary it is intended to cover various modifications and equivalent arrangement included within the spirit and scope of the claims which follow.